

Electroactive polymers (EAP) as Emerging Technology for Devices and Robotics

Review, Capabilities, Applications and Potential



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Outline

- EAP background and what are the alternatives
- Electroactive polymers as artificial muscles
- What are the currently available EAP materials and their properties?
- EAP application considerations
- Future development and applications

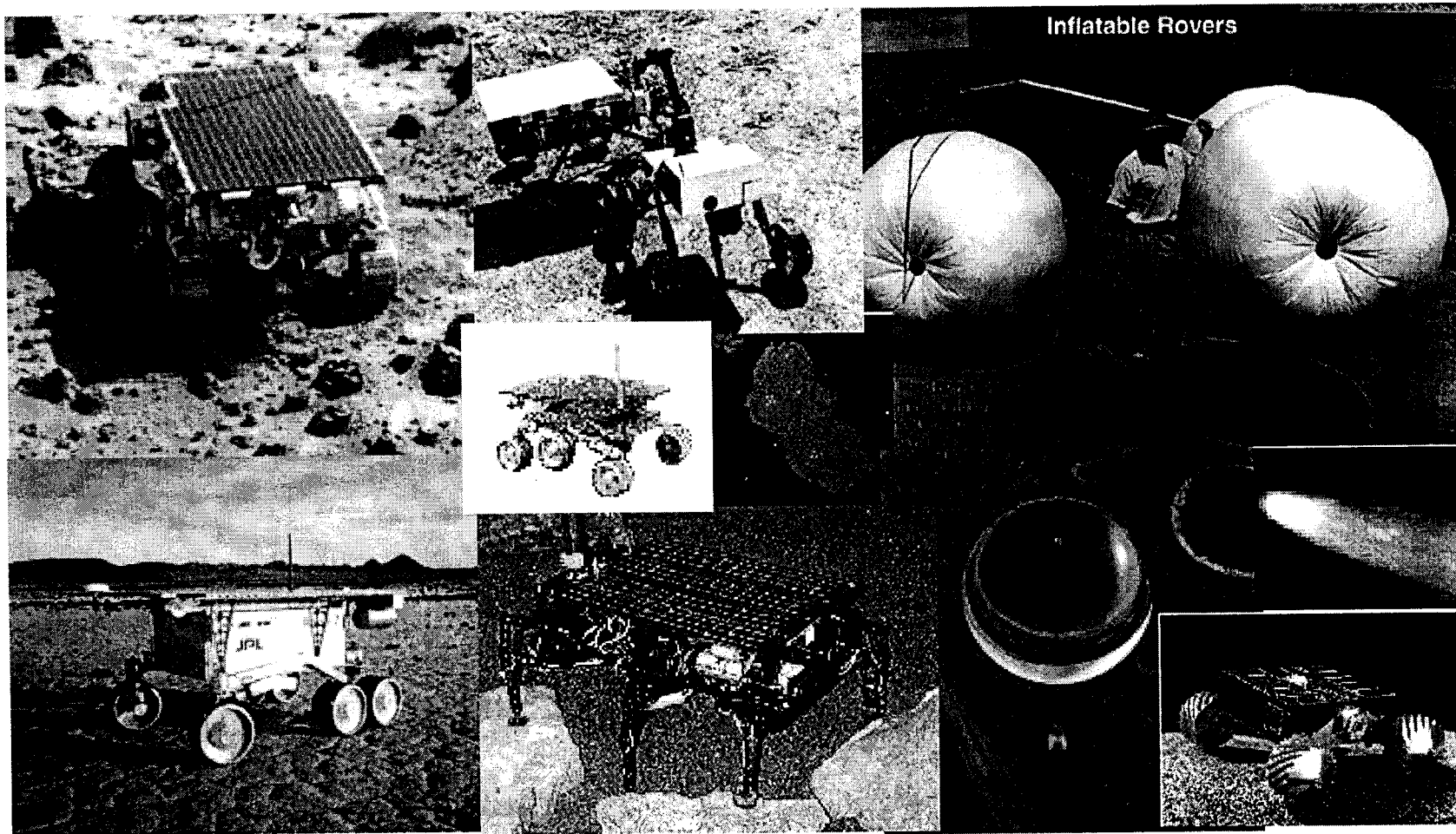
What is an Electroactive Polymer (EAP)

- EAP materials are polymers that exhibit change in a property or a material/physical characteristic as a result of an electrical stimulation (field, current, etc.).
- Changes can involve physical deformation, optical or magnetic variation and others.
- The emphasis of this course is on EAP materials that display electro-mechanical reaction.

Background

- Electroactive polymers (EAP) are emerging with behavior that mimic biological muscles.
- These materials can be used to produce actuators that are miniature, light, inexpensive, use low power and best of all induce large displacements.
- Tests have shown that certain EAP materials operate effectively also at cryogenic temperatures and vacuum.
- The technology enables unique actuation to support various mechanisms, robotics and locomotion needs.

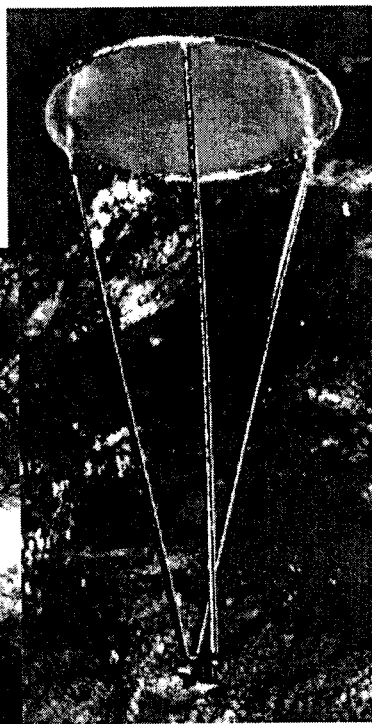
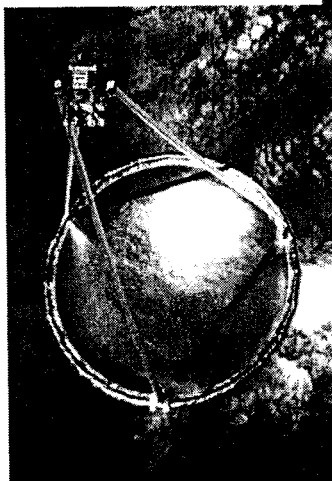
Rover technology at JPL



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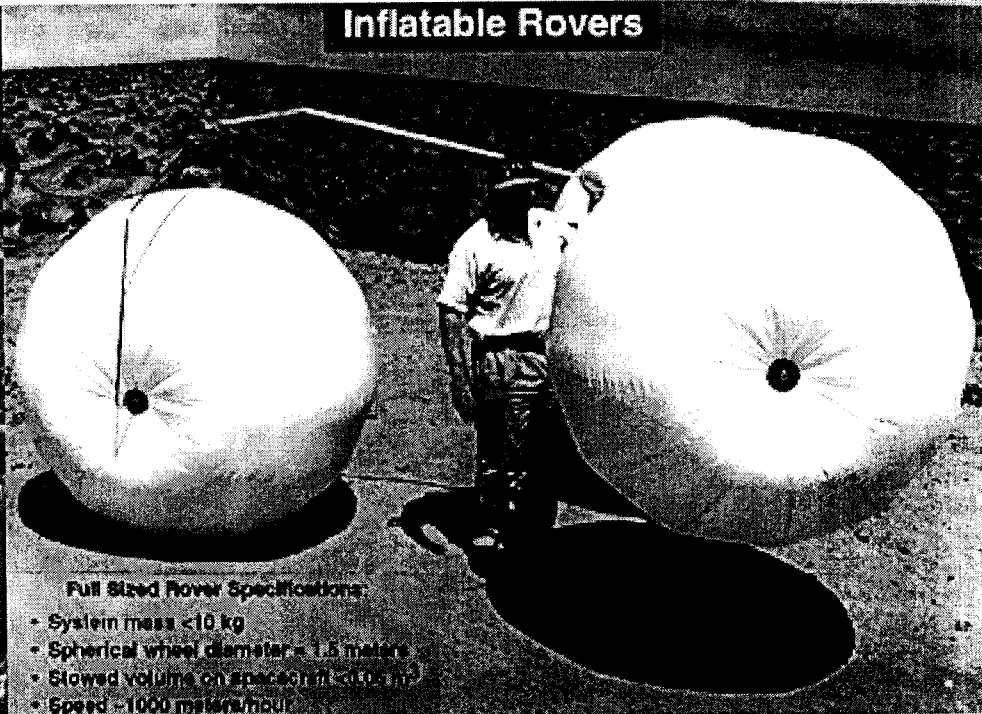
Inflatable structures

Inflatable antennas & telescopes



Inflatable vehicles

Inflatable Rovers



Alternative electroactive materials

- For many years, the leading actuation materials have been electroactive ceramics (EAC) and shape memory alloys (SMA).
- In contrast to EAC, EAP are emerging with >2 orders of magnitude displacement capabilities that cannot be matched by the striction-limited, rigid and fragile ceramics.
- In contrast to SMA, EAP responds significantly faster and have fatigue life many orders of magnitude longer.
- EAP are more compliant to mass-production, easy to configure in various shapes and potentially can be made at low cost.

Comparison between EAP and widely used transducing actuators

Property	EAP	EAC	SMA
Actuation strain	>10%	0.1 - 0.3 %	<8% short fatigue life
Force (MPa)	0.1 – 3	30-40	about 700
Reaction speed	μ sec to sec	μ sec to sec	sec to min
Density	1- 2.5 g/cc	6-8 g/cc	5 - 6 g/cc
Drive voltage	1-7V/ 10-100V/ μ m	50 - 800 V	NA
Consumed Power*	m-watts	watts	watts
Fracture toughness	resilient, elastic	fragile	elastic

* Note: Power values are compared for documented devices driven by such actuators.

Historical prospective

- The pioneering of the EAP field can be attributed to Eguchi's 1925 reported discovery of an electret material*.
 - Obtained when carnauba wax, rosin and beeswax are solidified by cooling while subjected to DC bias field.
- Another important milestone is the 1969 observation of a substantial piezoelectric activity in PVF2.
 - PVF2 films were applied as sensors, miniature actuators and speakers.
- Since the early 70's the list of new EAP materials has grown considerably, and the most progress was made in this decade.
 - This EAPAD conference of SPIE, initiated by its Chair, is the first conference on this subject.
- Even though many EAP were already introduced, the number of commercially used ones was mostly limited to PVF2/TRFE materials and ceramic/ polymer composites.

* Electrets are dielectric materials that can store charges for long times and produce field variation in reaction to pressure.

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BIOLOGICALLY INSPIRED ROBOTICS

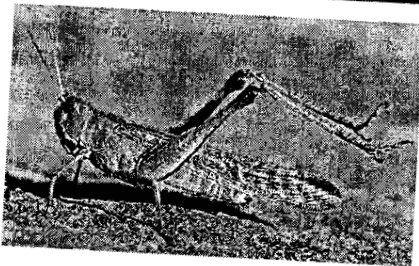
MULTI-TASKING IN-SITU MISSIONS USING SCALABLE AUTONOMOUS ROBOTS FOR COLONIZED PLANETARY EXPLORATION

Multiple locomotion capabilities

Flying,
walking,
swimming &
diving



Hopping,
flying,
crawling
& digging



Coordinated
robotics



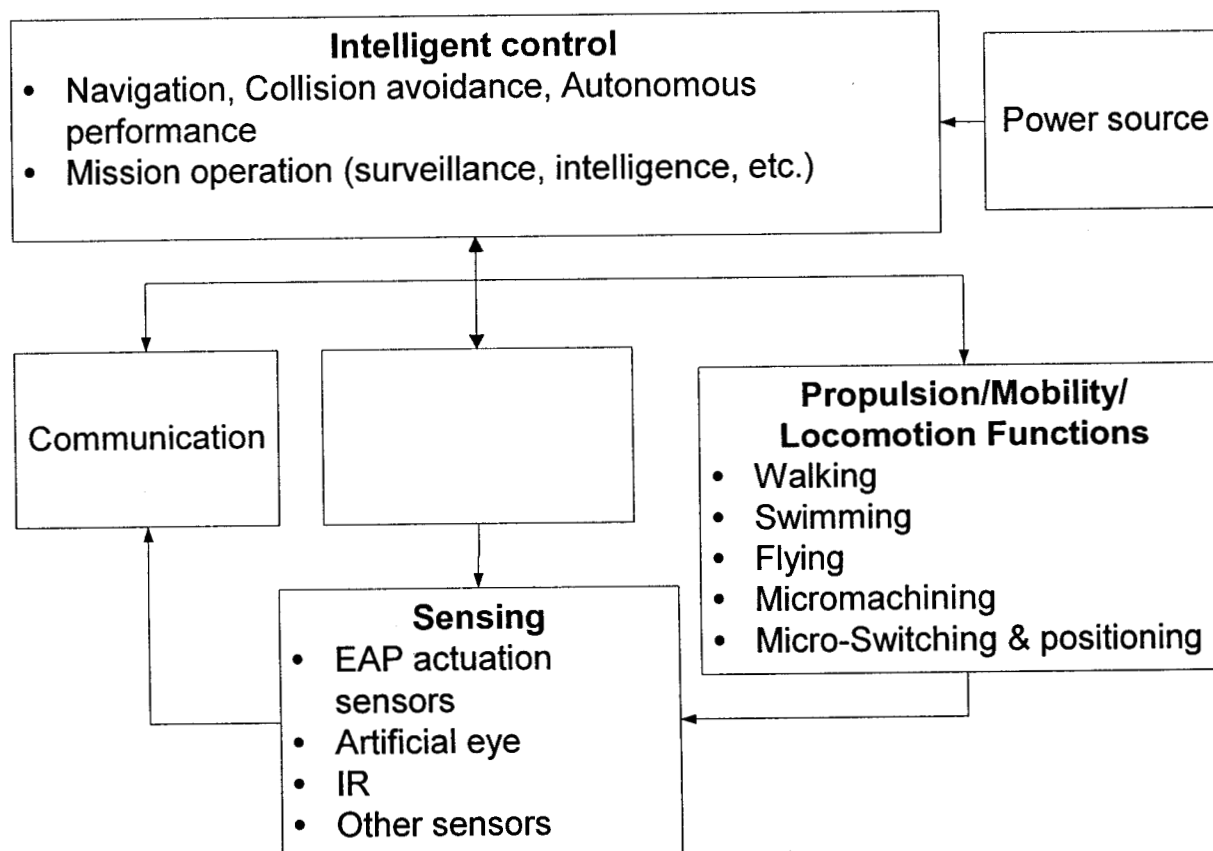
Examples from
nature offer ideas
for scalable
autonomous robots
that can be used to
colonize planets
and perform multi-
tasking in-situ
exploration
missions



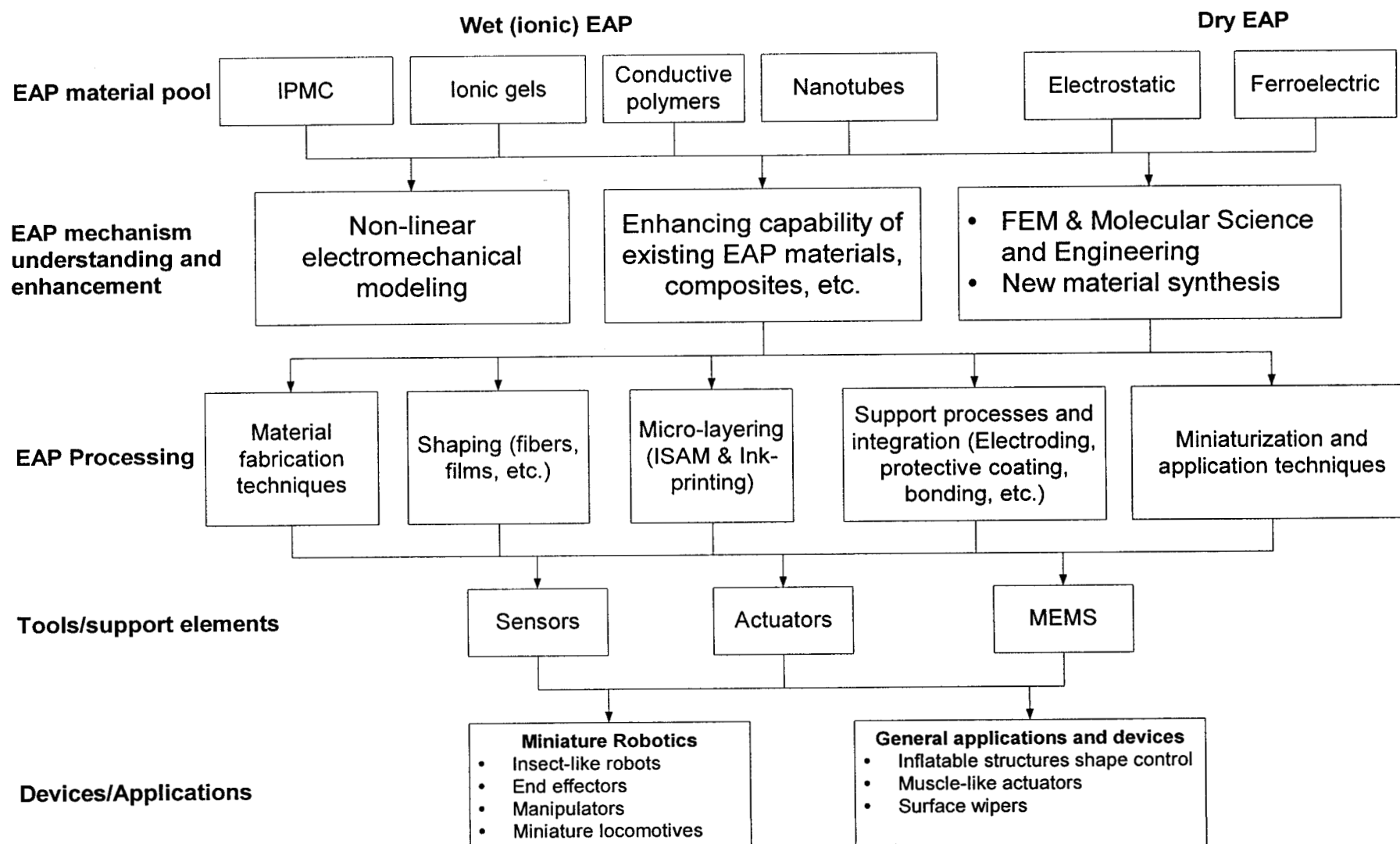
Potential EAP applications for robotics

- EAPs offers unique characteristics to produce highly maneuverable, noiseless, agile biomimetic miniature robots.
- EAP actuators can be used to produce mechanisms with simple drive signals but the nonlinear behavior needs to be taken into account.
- Such materials can be used to provide the necessary locomotion drive mechanism of insect-like (flying, crawling, swimming, etc.) robots at sizes that range from microns to several centimeters.
- The development and application of EAP materials and mechanisms involves interdisciplinary expertise in chemistry, materials science, electronics, mechanisms, computer science and others.

Elements of an EAP actuated system



EAP infrastructure



Wet (Ionic) Electroactive Polymers

Actuator type	Principle	Advantages	Disadvantages	Reported types
Ionic Conductive Polymers (ICP)	Materials containing solvated ions that cause swelling in response to an applied voltage	Use low voltage	Need surface protection to operate in dry environment	Polypyrrole, Polyethylenedioxythiophene, Poly(p-phenylene vinylene)s, Polyaniline, and Polythiophenes
Ionic gels	Generally, activated by a chemical reaction (changing from acid to base causing increased density or swelling, respectively)	Potentially capable of matching the force and energy density of biological muscles	Operates very slowly and would require very thin layers and new type of electrodes to become practical	Polyacrylamide/Electrode/ Polyacrylamide/ Polyacrylic acid/Electrode/ Polyacrylic acid
Ion-Exchange Polymer Metal Composites (IPMC)	Bending is stimulated in IPMC, where the base polymer provides channels for mobility of positive ions in a fixed network of negative ions on interconnected clusters	<ul style="list-style-type: none"> Activated by low voltage Provides significant bending 	<ul style="list-style-type: none"> Operates at low frequency. Sensitive to dehydration and developed coating is ineffective. Subject to permanent deformation under DC Subject to hydrolysis above 1.23V 	<u>Base polymer:</u> <ul style="list-style-type: none"> Nafion® (perfluorosulfonate made by DuPont) Flemion® (perfluorocaboxylate, made by Asahi Glass, Japan). <u>Cations:</u> tetra-n-butylammonium, Li ⁺ , and Na ⁺ <u>Metal:</u> Pt and Gold
Carbon Nanotubes	Using nanometer size tubes that are ionically activated. Showed induced strains of < 1% along the length and ~300% laterally	<ul style="list-style-type: none"> Potentially provide superior work/cycle & mechanical stresses Carbon offers high thermal stability towards >1000°C 	<ul style="list-style-type: none"> Expensive. Difficult to produce in large quantities 	Carbon

Dry Electroactive Polymers

Actuator type	Principle	Advantages	Disadvantages	Reported types
Ferroelectric Polymers	<ul style="list-style-type: none"> PVDF is involved with large dielectric loss. Application of electron radiation onto a P(VDF-TrFE) copolymer introduces defects into the crystalline structure dramatically lowering the dielectric losses. 	<ul style="list-style-type: none"> Demonstrates electrostrictive behavior The relatively high elastic modulus offers high mechanical energy density Induces relatively large strain (~5%) [being considered for sonar transducers]. This permits AC switching with a lot less generated heat. 	Requires high voltage (~150 MV/m)	Electron radiated P(VDF-TrFE)
Electro-Statically Stricted Polymers (ESSP)	<ul style="list-style-type: none"> Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting them to an electrostatic field. Coulomb forces between the electrodes squeezes and stretching the EAP material 	<ul style="list-style-type: none"> Large displacements reaching levels of 200% Rapid response 	<ul style="list-style-type: none"> Requires large voltage. Obtaining large displacements compromises the actuation force 	<ul style="list-style-type: none"> Silicone Polyurethane

Advantages and disadvantages

Current EAP

EAP type	Advantages	Disadvantages
Dry	<ul style="list-style-type: none">• Can operate in room conditions for a long time• Can respond at very high frequencies• Provides large actuation force	<ul style="list-style-type: none">• Requires high voltages• A compromise is needed between strain and stress
Wet (Ionic)	<ul style="list-style-type: none">• Provides mostly bending actuation (longitudinal mechanisms can be articulated)• Large bending displacements• Sustain hydrolysis at $>1.23\text{-V}$• Requires low voltage	<ul style="list-style-type: none">• Does not hold strain under DC voltage• Operates at low frequencies (several Hertz)• Bending EAP presents a very low actuation force

Electroactive Actuators- Database

EAP Type (specific example)	Maximum Strain (%)	Maximum Pressure (MPa)	Specific Elastic Energy Density (J/g)	Elastic Energy Density (J/cm ³)	Coupling Efficiency k^2 (%)	Maximum Efficiency (%)	Specific Density G/cc	Relative Speed (full cycle)
Electrostatically actuated: Silicone (CF19-2186)	63	3.0	0.75	0.75	63	90	1	Fast
Electrostrictor Polymer (P(VDF-TrFE))	4	15	0.17	0.3	5.5	–	1.8	Fast
Piezoelectric Polymer (PVDF)	0.1	4.8	0.0013	0.0024	7	n/a	1.8	Fast
Shape Memory Polymer	100	4	2	2	–	< 10	1	Slow
Thermal (Expansion)	1	78	0.15	0.4	–	< 10	2.7	Slow
Electrochemo-mechanical Conducting Polymer (Polyaniline)	10	450	23	23	< 1	< 1%	~1	Slow
Mechano-chemical Polymer/Gels (polyelectrolyte)	> 40	0.3	0.06	0.06	–	30	~1	Slow
Natural Muscle (Human Skeletal)	> 40	0.35	0.07	0.07	n/a	> 35	1	Medium

Source: SRI International data, 9/16/99

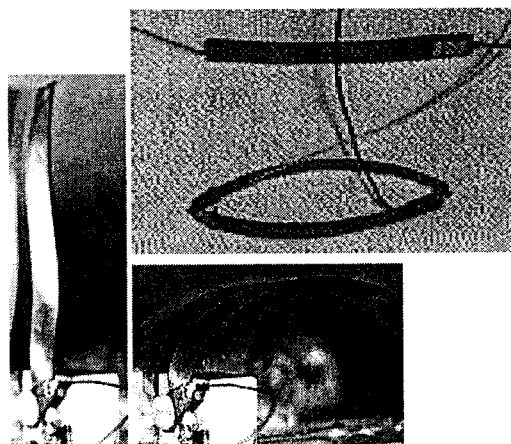
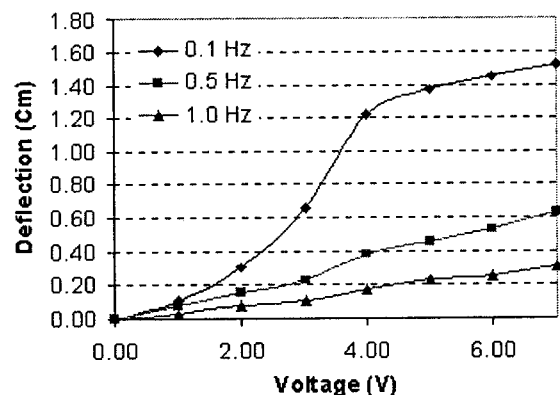
Web: <http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/actuators-comp.pdf>

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Technology status

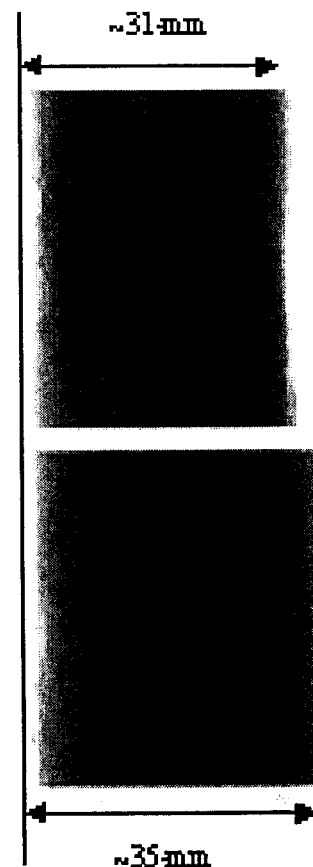
- Bending and longitudinal EAP actuators are developed by numerous research institutes, academia and industry.
- Various unique capabilities and applications are investigated.
- EAP changed the paradigm about robotics construction - polymer materials can serve simultaneously as a structural element, actuator and end-effector.
 - Conventional robots are driven by mechanisms that consist of motors, gears, bearings, etc.
 - Electroactive polymers (EAP) offer alternative simple and direct actuation with resilience and toughness emulating biological muscles.
- The limiting factor to their potential application for space, medical, commercial, military and other areas is their low force actuation force.

Bending and longitudinal EAP *Examples*



Ion-exchange Polymer membrane Metallic Composite (IPMC) can bend by over 90° under ~3-4V and ~30-50-mW.

31-mm wide, 50-μm thick Electrostatically stricted polymer (ESSP) film extending over 12%

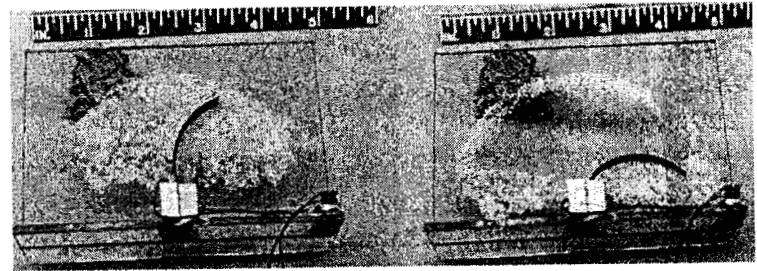


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EAP mechanisms developed at JPL

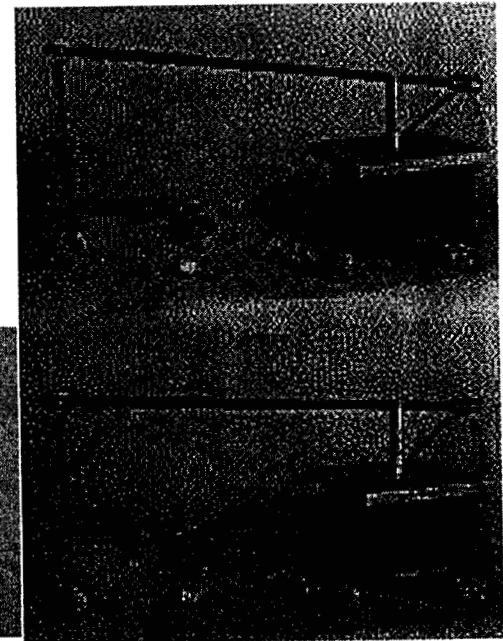
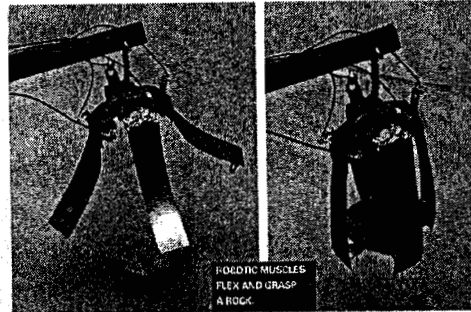
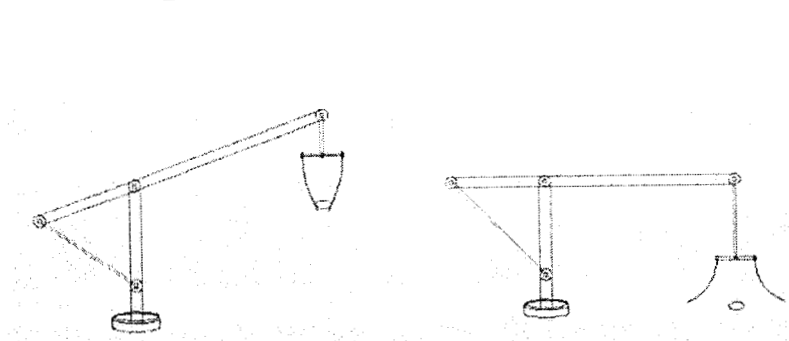
Dust wiper

A bending EAP is being developed as a dust wiper for application considerations in the MUSES-CN mission



Miniature robotic arm

A stretching EAP is used to lower a robotic arm, while bending EAP fingers operate as a gripper. The technology is being developed to enable miniature sample handling robotics.



Longitudinal EAP Actuators

Electro-Statically Stricted Polymer (ESSP)

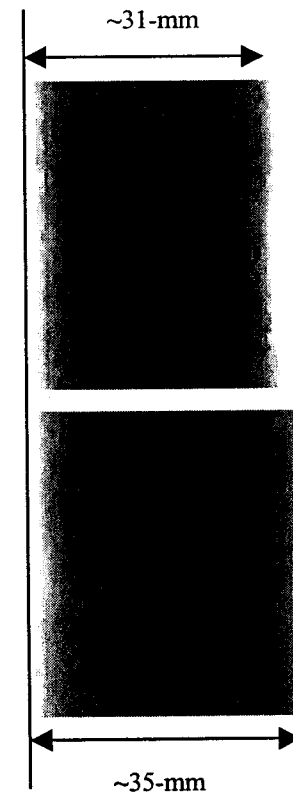
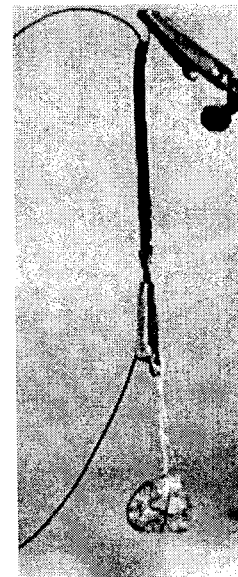
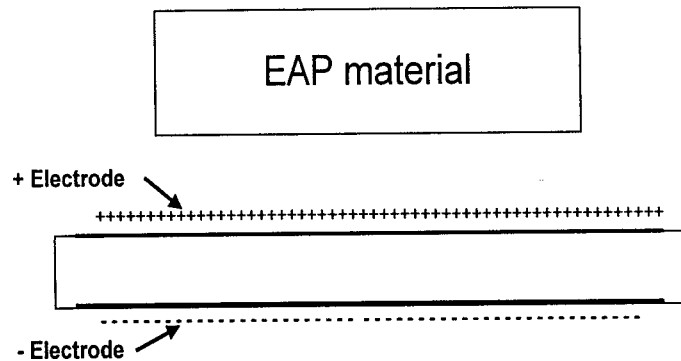
- Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting them to an electrostatic field.
- Coulomb forces between electrodes can squeeze or stretch a sandwiched polymer material.
- Longitudinal electrostatic actuator can be made of a dielectric elastomer film (silicone) coated with carbon powder electrodes.
 - The force (stress) that is exerted on such a film with compliant electrodes is:

$$P = \epsilon \epsilon_0 E^2 = \epsilon \epsilon_0 (V / t)^2 \quad (1)$$

Where: P is the normal stress, ϵ_0 is the permittivity of vacuum and ϵ is the relative permittivity (dielectric constant) of the material, E is the electric field across the thickness of the film, V is the voltage applied across the film and t is the thickness of the film. The Poisson's ratio is assumed as 0.5.

Longitudinal EAP actuator *Electro-Statically Stricted Polymer (ESSP)*

Under electro-activation, a polymer film with electrodes on both surfaces expands laterally.

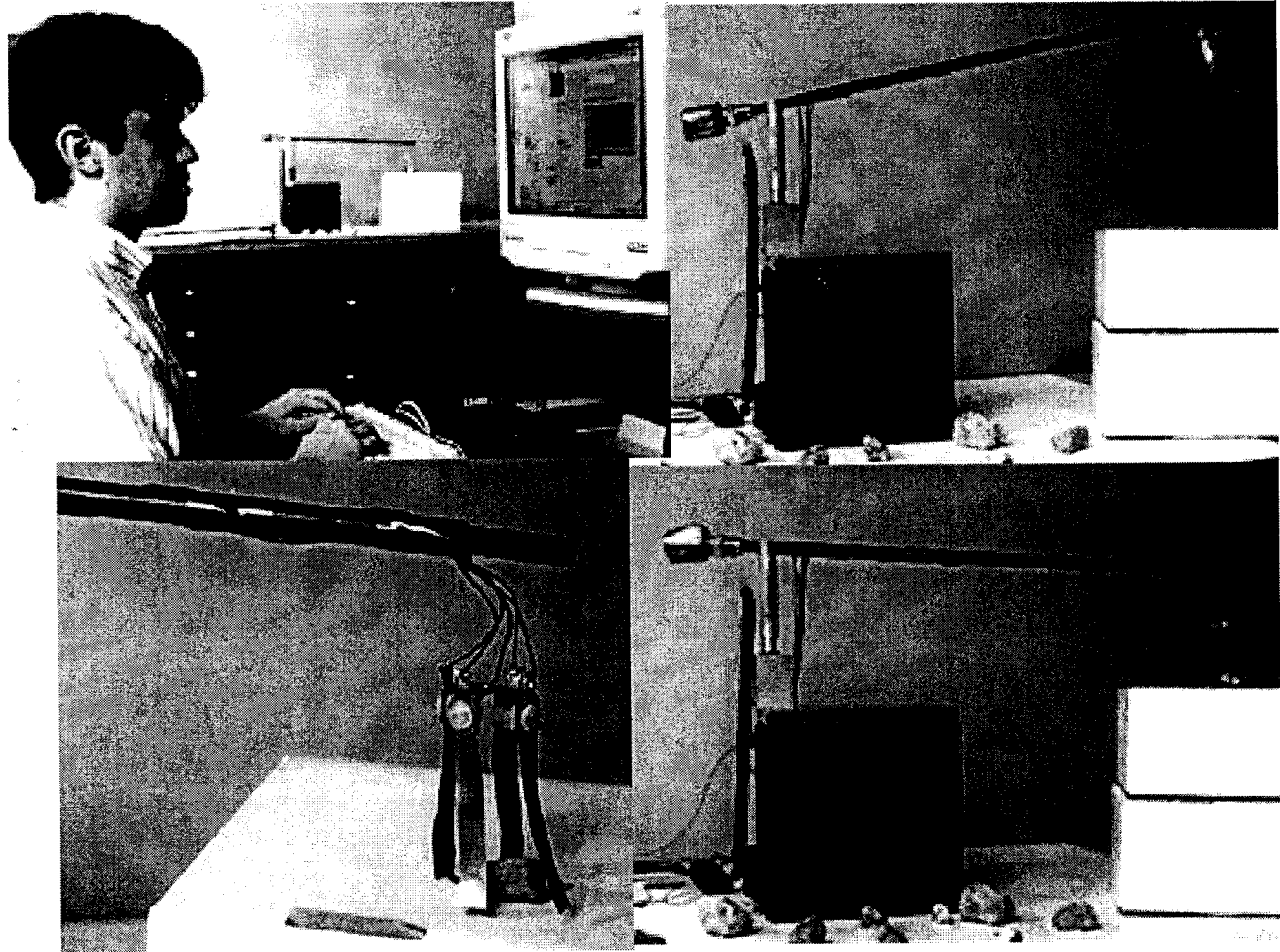


EAP film subjected to $25 \text{ V}/\mu\text{m}$
induced over 12% extension

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Robotic arm

**A computer
controlled arm
with
longitudinal
EAP actuator
serving as the
lifter and
bending EAP
fingers as the
gripper**



YB23

Electro-Statically Stricted Polymer (ESSP)

- Polymers with high dielectric constants and application of high electric field leads to large actuation forces and strains.
 - Under an electric field the film is squeezed in the thickness direction causing expansion in the transverse direction.
 - For a pair of electrodes with circular shape, the diameter and thickness changes can be determined using the following relation, where the second order components are neglected.

$$\Delta D / D_0 = -(1/2)\Delta t / t_0 \quad (2)$$

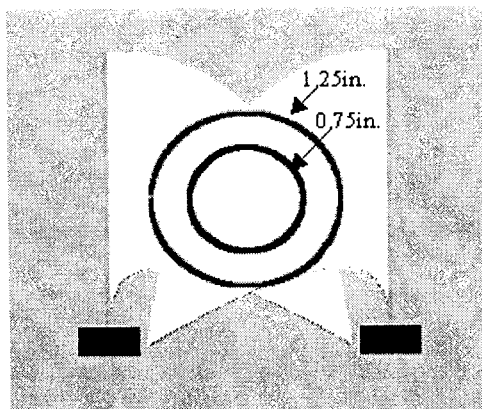
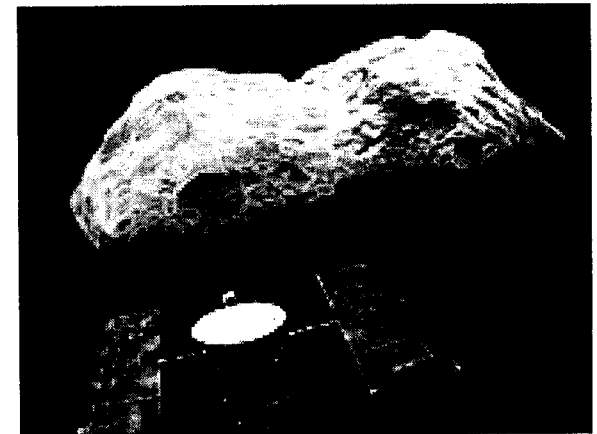
Where: D_0 is the original diameter of the electrodes and ΔD is the resultant diameter change, t_0 is the original thickness and Δt is its change under electric activation.

- Enhancement of the actuation capability is expected from electrostrictive polymers. Such polymer offers, in addition to the effect of the Coulomb forces, also inherent contraction of the polymer.

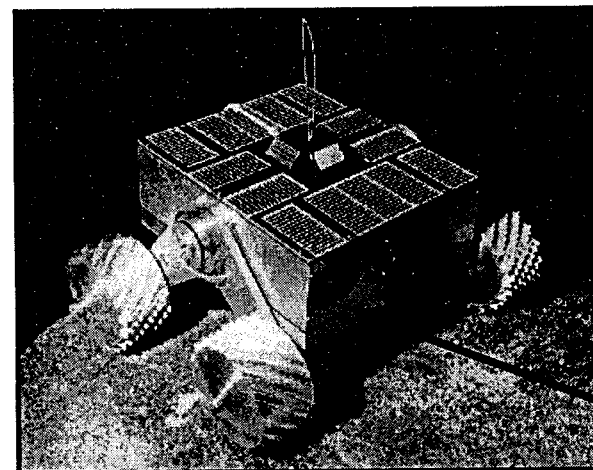


MUSES-CN Mission, the Nanorover and the EAP dust-wiper

- The MUSES-CN mission is planned for launch to an Asteroid in 2002.
- A probe will be dropped on the asteroid and blast-off dust.
- The imaging capability of the Nanorover will be affected by the dust.
- Pair of EAP wipers is based lined to remove the dust.



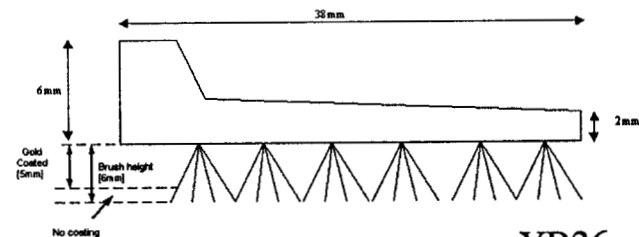
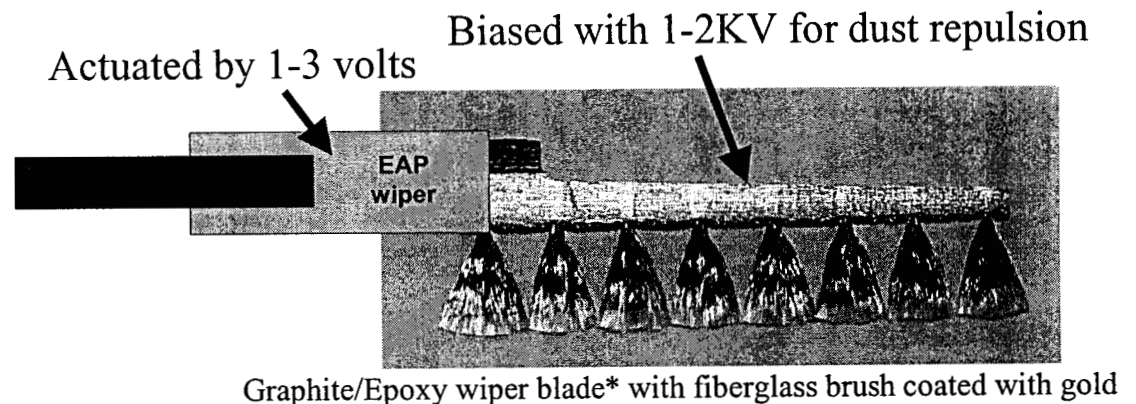
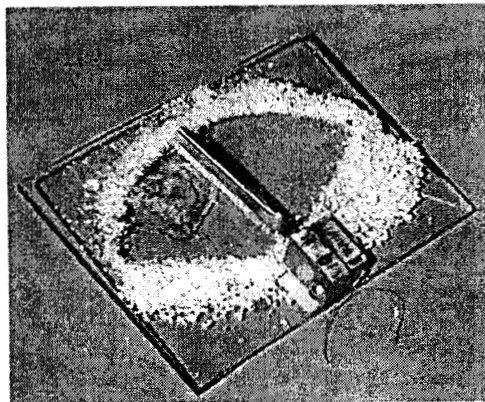
Simulated window and 2 side dust wipers



Imaging window YB25

EAP actuated dust wiper

- Flight-like EAP dust wiper is being prepared at JPL using specifications of the MUSES-CN mission
- LaRC developed a unique protective coating
- ESLI developed effective wiper blades
- Osaka National Research Institute, Japan, is providing effective bending EAP
- Kobe University, Japan, is providing electromechanical modeling assistance
- VT is developing a self-assembled mono-layering technique for improved electroding

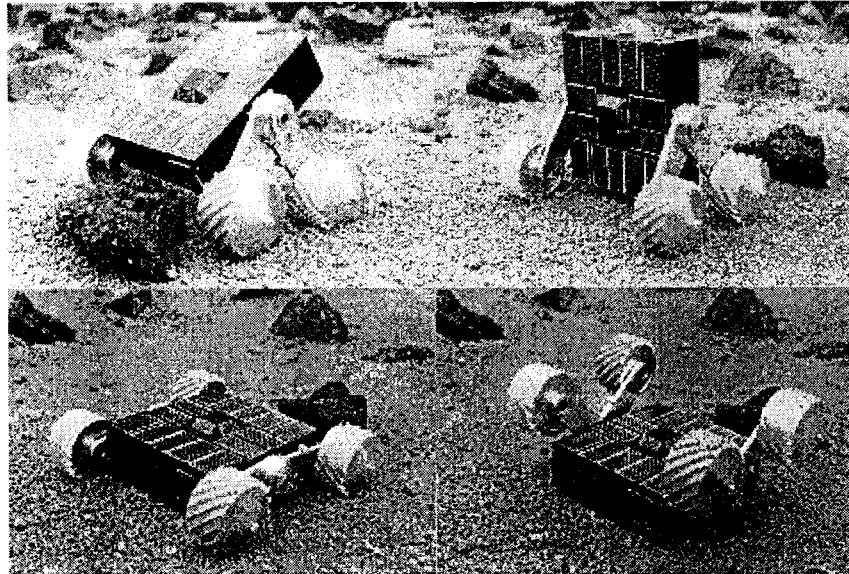


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* Made by Energy Science Laboratories, Inc., San Diego, California

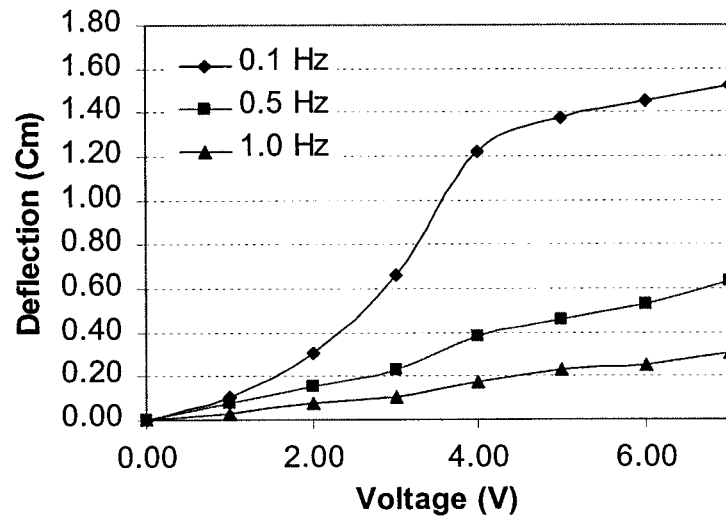
Planetary technical challenges

NanoRover

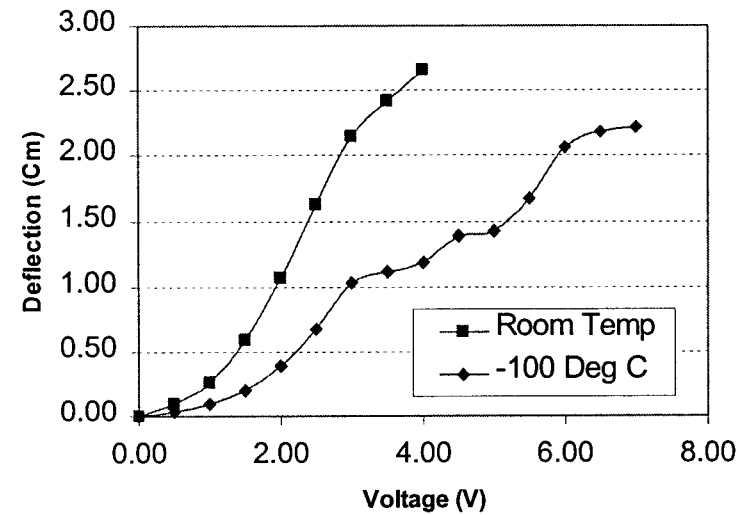


- Mars exploration requires removal of dust as small as $3.2\mu\text{m}$ diameter.
- Operation on an asteroid (MUSES-CN mission) requires addressing the effect of ionic radiation, UV and a large temperature range.
 - Overall the temperature range is: -155°C to $+125^{\circ}\text{C}$ and the desired operating range is -125°C to $+60^{\circ}\text{C}$

IPMC as a bending EAP actuator



Room temperature response



Response at Cryovac

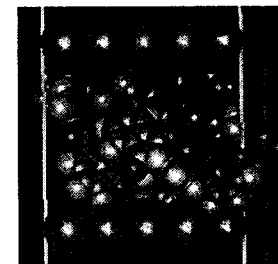


Challenges and solutions to the application of IPMC as bending actuators

Challenge	Solution
Fluorinate base - difficult to bond	Apply pre-etching
Sensitive to dehydration	Apply protective coating over pre-etched IPMC
Off-axis bending actuation	Constrain the free end
Operate at low temperatures	IPMC was demonstrated to operate at -140°C
Remove small size dust	Use effective wiper-blade design and high bias voltage
Protective coating is permeable	Develop alternative coating possibly using overcoat
Low actuation force	Need enhancement of material performance
Complex equivalent circuit characteristics	Need improved understanding
Reverse bending under DC voltage	Limit application to dynamic operations
Electrolysis occurs at >1.23-V causing blisters under the coating	Use efficient IPMC requiring lower actuation voltage
Residual deformation	Still a challenge
No established quality assurance	Use short beam/film and tackle the critical issues

Enhancement issues

- One of the major shortcomings of EAP is their relatively low force actuation capability, falling way shorter than biological muscle.
- To enhance the actuation force, materials science and electromechanics as well as engineering issues require adequate attention.
 - Computational chemistry modeling is needed to allow methodic design and synthesis of new effective EAP materials.
 - Comprehensive mechanics modeling is needed to analyze the non-linear behavior.
- The processes of synthesizing, fabricating, electroding, shaping and handling EAPs needs to be refined to maximize EAP's actuation capability and robustness.



FEM Computational chemistry of EAP

- The improvement of the induced force capability of EAP is critical to making these materials the actuators of choice.
- Recent work at the NASA LaRC's Computational Materials Program used accurate quantum chemistry calculations to determine force fields for a range of polymers including polyimides.
- The calculated force field was experimentally verified (through thermo-physical and ultrasonic measurements).
 - The method was used to predict response to electric fields, mechanical stresses, and temperature.
- Planes of large spheres represent the metal electrodes, and are used to simulate the poling field. The properties from atomistic simulations are fed into large-scale finite-element models.
- So far, successful models at the atomistic, micro-mechanical, and continuum levels have been developed.

Modeling EAP large strain actuation

- Effective design of EAP mechanisms with large actuation strains, requires analytical tools that can address the nonlinear behavior.
- Generally, the constitutive relations for electroactive materials can be adequately described by means of equations of the form:

$$D_i = \varepsilon_{ij} E_j + 2m_{ijkl} E_j \sigma_{kl}, \quad e_{ij} = m_{ijkl} E_k E_l + s_{ijkl} \sigma_{kl}$$

Where: \mathbf{D} is the electric displacement vector, \mathbf{E} is the electric field vector, \mathbf{e} is the strain tensor and σ is the stress tensor. The coefficient matrices and tensors of the equation are material constants that need to be determined through laboratory tests.

- The mechanical response to a given electrical field is determined from a suitable equation of motion supplemented by these constitutive relations.
- A distinguishing feature of electrostrictive materials is the presence of the nonlinear (quadratic) terms in \mathbf{E} .

Modeling EAP large strain actuation (Cont.)

- The constitutive equations are linear in the strains and, therefore, can only be used to analyze “small displacement” actuators.
- Certainly, EAP strain is not “infinitesimal,” and the quasi-linear constitutive relations may not be adequate to predict the electro-mechanical behavior.
- An alternative system of constitutive relations is needed that includes the nonlinear terms in the strain and the electric fields.
 - The nonlinear constitutive relations needs to contain quadratic terms in both \mathbf{E} and \mathbf{e} based in thermodynamic principles.



Significant future applications

Mechanisms & Robotics

Muscle actuators that are resilient and damage tolerant will enable:

- Walking, crawling, swimming and/or flying miniature robots
- Insect-like robotic colonies that emulate ants.

Miniaturization

MEMS using EAP actuators and sensors.

Planetary applications

Recent JPL results, showing that bending-EAP are operating at low-temperatures and vacuum, have a great promise for space applications such as:

- EAP surface wiper for dust removal from optical/IR windows
- Miniature robotic arm for sample manipulation
- Under consideration: Support active/controllable inflatable structures

Transition to broad range of applications

Beneficiaries include: medicine, consumer products and military.

Summary

- Electroactive polymers (EAP) are emerging with capabilities that mimic biological muscles.
 - Inducing large displacements and can be made miniature, low mass, inexpensive, and consume low power.
- The technology enables unique actuation for various mechanisms, robotics and locomotion capabilities.
- The infrastructure of the field needs to be enhance and international collaboration among the developers and users is expected to lead to great improvement in the coming years.
 - Issues associated with their low force actuation capability and non-linear behavior requires attention.
 - Effective sensors are needed to track the large displacement as well as provide position information.
 - The resilience of the material and flexibility of the material poses control problems



The grand challenge for EAP as ARTIFICIAL MUSCLES



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